

# Detection of vegetation change using reconnaissance imagery

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## Abstract

**Vegetation occurs at its highest elevations on equatorial mountains. Inspection of archival and recent high-resolution reconnaissance imagery of tropical mountains shows, in all cases, features indicating an increase in the elevation of mountain vegetation zones and an increase in vigour in the high-elevation vegetation. These changes are consistent with an increased plant performance from increased levels of carbon dioxide in the atmosphere as well as with a warmer or more favourable climate.**

*Keywords:* carbon dioxide fertilization, high-elevation vegetation, Mt. Kenya, Mt. Kilimanjaro, reconnaissance imagery, vegetation change

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## Introduction

In 1992, at the urging of then Senator, now Vice President Gore, the CIA established an Environmental Task Force (ETF) to pursue opportunities for exploiting the technical assets of the Intelligence Community to address environmental problems. To support this task force, 60 US scientists, known as MEDEA, were given security clearance to use classified data. MEDEA found that a relatively modest commitment of resources, combined with information collected from technical intelligence assets already in place, could yield dividends for environmental scientists. One of the issues identified as important to MEDEA was global climate change: primarily, how may information collected from technical intelligence assets be used to help answer some of the questions currently being asked related to global climate change? This paper is an example of an initial project designed to explore the use of reconnaissance imagery to detect changes in vegetation zones. Our motivation was to inspect locations that potentially might be responsive to elevated levels of atmospheric CO<sub>2</sub>, and we shall

present our rationale for choosing high-elevation locations in the text that follows. As is the case with observational data, we have not demonstrated that elevated CO<sub>2</sub> is altering vegetation in these locations. Indeed, elevated CO<sub>2</sub> levels are consistent with our observations, but not uniquely so.

A striking change associated with modern human society has been the increase in atmospheric CO<sub>2</sub> associated with the increased burning of fossil fuels (coal, petroleum, natural gas) since the industrial revolution (Sarmiento & Siegenthaler 1992; Sarmiento & Bender 1994). Because CO<sub>2</sub> is an essential component of plant photosynthesis, the observation of a systematic increase in ambient CO<sub>2</sub> levels immediately leads to the question of whether these changes might be altering plant function globally and producing changes in patterns of vegetation.

We inspected national reconnaissance imagery<sup>1</sup> to find changes in degree of cover in mountain vegetation, in very high-elevation equatorial locations around the world. It has been argued that these locations are the most likely to demonstrate a vegetation response to the increased levels of CO<sub>2</sub> in the atmosphere (LaMarche *et al.* 1984; Graumlich 1991; Woodward & Bazzaz 1998). Vegetation at the three sites that we studied all display

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<sup>1</sup>Information about the declassified (DISP) imagery used in this analysis can be found at: [HTTP://edcwww.cr.usgs.gov/Webglis/glisbin/guide/pL/glis/hyper/guide/disp](http://edcwww.cr.usgs.gov/Webglis/glisbin/guide/pL/glis/hyper/guide/disp)

evidence of increasing plant vigour or of up-slope movement of vegetation zones. We present results from two sites, Mt. Kenya in Kenya and Mt. Kilimanjaro in Tanzania. These investigations were undertaken initially to determine whether there was measurable vegetation change consistent with increased ambient atmospheric CO<sub>2</sub>; however, it is difficult to discount other global climatic trends to explain our results. Our results establish that reconnaissance imagery can be used to monitor historical and future changes in high-elevation plant communities, which are potentially more responsive to CO<sub>2</sub> change, and which demonstrate significant change in the areas we studied.

### High-elevation vegetation as a potential indicator of direct CO<sub>2</sub> effects on plants

LaMarche *et al.* (1984) reported elevated rates of growth in bristlecone pines (*Pinus longaeva* and *P. aristata*) from high-elevation sites from New Mexico, Colorado and California. They found an increase in tree ring-width occurred between 1840 and 1970, which they interpreted as the first documented response of natural-vegetation growth-enhancement from the increase in atmospheric CO<sub>2</sub>. In addition, they reported increased growth rings for another high-elevation species, limber pine (*P. flexilis*) in central Nevada which showed a similar pattern with a continued or even accelerated growth rate increase in the 1970s. These patterns were corroborated by the collection of additional bristlecone pine data from two upper tree line sites located in the White Mountains of Eastern California (LaMarche *et al.* 1984). Later studies in Nevada (Graumlich 1991) measured tree ring growth indices in other species of subalpine coniferous trees (foxtail pine, *P. balfouriana*; lodgepole pine, *P. murrayana*; western juniper, *Juniperus occidentalis*), but failed to find such a trend in 3 of 5 locations.

LaMarche *et al.* (1984) noted that higher elevation locations have lower partial pressures of CO<sub>2</sub> reducing the gradient and, hence, a reduced rate of diffusion of CO<sub>2</sub> through the leaf stomata (see also Tranquillini 1979). They reasoned that plants at higher elevations are more likely to be limited by CO<sub>2</sub> and more likely to respond positively to increased CO<sub>2</sub> levels. Cooper (1986) and Gale (1986) both criticized this view, citing possible complicating factors as well as theoretical considerations, but were rejoined by LaMarche *et al.* (1986), who pointed to earlier experimental work (Mooney *et al.* 1964; Mooney *et al.* 1966) indicating differences photosynthesis rates in plants grown at different elevations (lower rates of photosynthesis at higher elevations). Subsequently, Körner & Diemer (1987) inspected 112 pairs of plant species at elevations of 600 and 2600 m in the Austrian Alps and found that alpine plants appeared to profit

more from elevated CO<sub>2</sub> levels than lowland plants of the same species.

Woodward (1987) found that the numbers of stomata per unit area on plant leaves have varied inversely in relation to the change in CO<sub>2</sub> concentration since the industrial revolution (around 1860). Change in stomatal density could potentially modify the stomatal resistance to fluxes of H<sub>2</sub>O and CO<sub>2</sub> and thus the plant water-use efficiency (the ratio of carbon fixed by photosynthesis to water used for transpiration). Stable isotope analysis of carbon in the same herbarium leaf samples was used to calculate the ratio of <sup>13</sup>C/<sup>12</sup>C as an index of the CO<sub>2</sub>-diffusivity (1993), and the ratio of <sup>13</sup>C/<sup>12</sup>C was found to have changed systematically since the industrial revolution and was associated with the observed reduction in stomatal density. Woodward (1987) was able to duplicate the changes in stomatal index he observed in archival plant specimens by using modern plants grown under altered partial pressures of CO<sub>2</sub> under experimental conditions (also see Woodward & Bazzaz 1998). Körner (1988) inspected the leaves from 200 plant species and found no systematic trends in the change in stomatal density over 7–12 decades (depending on the species), or from lowland vs. alpine plants. However, Körner *et al.* (1988) did find that the <sup>13</sup>C/<sup>12</sup>C ratio in leaves of over 100 plant species (or ecotypes) from several different mountain ranges had increased <sup>13</sup>C content with elevation. This reduced discrimination against <sup>13</sup>C indicates decreasing relative limitation of carbon uptake by carboxylation. Based on theoretical considerations regarding <sup>13</sup>C discrimination, one would estimate a lower ratio of internal to external CO<sub>2</sub> ( $p_i/p_a$ ) in higher elevation plants from these data, and a consequent gradient-related reduction of the rate of inward diffusion of CO<sub>2</sub>. Street-Perrott *et al.* (1997) inspected ratios of C isotopes in sediments of African lakes deposited in sediments for the last 20000 years. The  $\delta^{13}\text{C}$  values from high-elevation lakes during the last glacial maximum indicated a severe carbon limitation on the plants. This supports the conclusion that tropical tree lines in the past were influenced significantly by carbon limitation and indicated a need to reassess the use of tropical tree-line variation for palaeotemperature reconstruction.

These earlier studies indicate that the long-term monitoring for changes in the vegetation found at higher elevations could be a useful means of detecting vegetation change in response to changes in atmospheric CO<sub>2</sub>. Because of other possible environmental changes with elevation, the need is for long-term sampling for synchronous vegetation change on multiple sites on a global basis. Because vegetation reaches its highest elevations on mountains in the equatorial tropics, any arguments regarding the effects on plants of altered

partial pressures of CO<sub>2</sub> should be more observable in these climates.

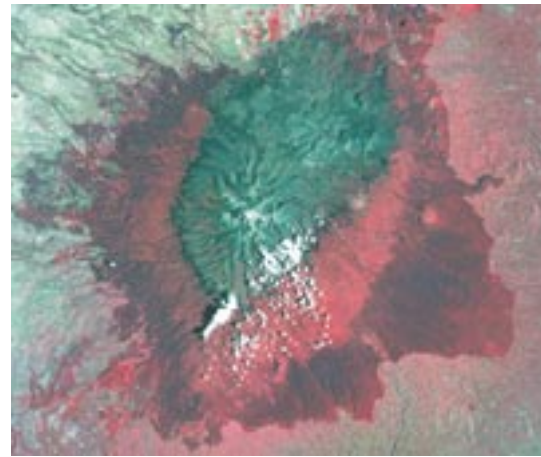
### *Measuring vegetation change on high-elevation equatorial mountains*

When asked by MEDEA to develop an archival observational network using reconnaissance imagery, we recommended the monitoring of the vegetation zones in the highest of the equatorial mountains for possible detection of a vegetation signal from increasing CO<sub>2</sub>. As a precursor to implementing such a global monitoring network, we undertook to determine whether or not vegetation in such locations could be characterized using reconnaissance imagery and whether vegetation change could be detected at such locations using this data. An initial problem was that the rates of changes observed at local study sites in mountains indicate relatively small spatial changes in vegetation zones (Franklin *et al.* 1971; Sprugel 1976; Marr 1977; Kullman 1986; Slayter & Good 1990; Noble 1993). Furthermore, equatorial tall mountains are often cloud covered, particularly at their summits, and are thus poor targets for remote sensing applications.

Searching over a number of potential study areas, we found three locations with archived imagery sufficient to allow inspection for change for time periods that were longer than a decade. We selected symmetrical mountains close to the equator and avoided sites on or near active volcanoes. Results from two of the study areas, Mts. Kenya and Kilimanjaro in Africa, are reviewed here.

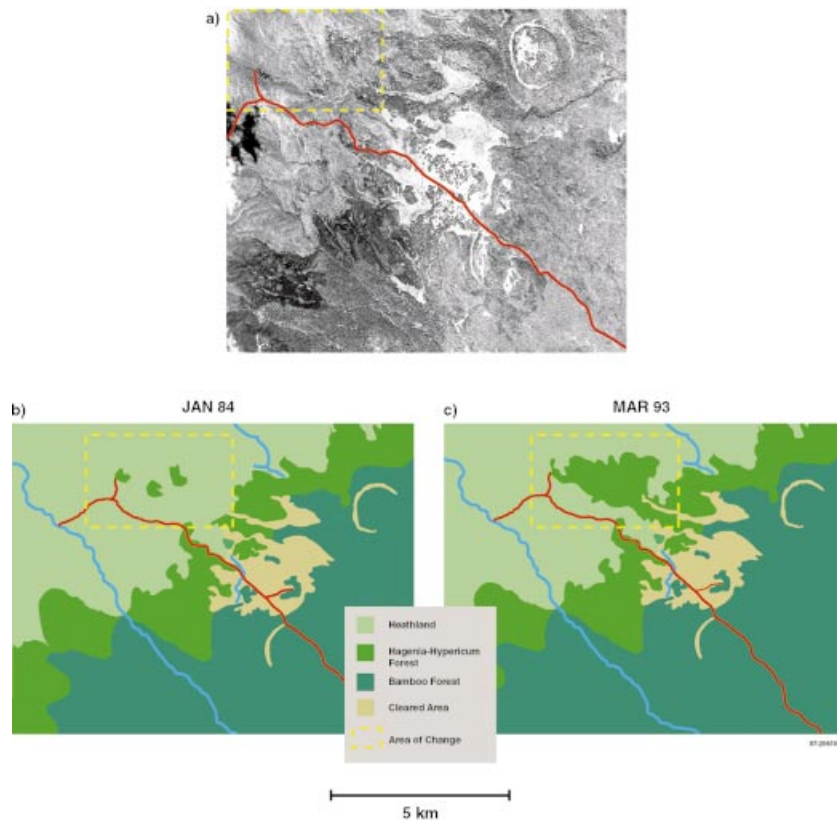
Our goal was to determine whether high-resolution imagery could be used to monitor vegetation change. We selected sites for this demonstration that were in locations where the vegetation might be particularly responsive to elevated CO<sub>2</sub> levels in the atmosphere, such as high-elevation equatorial sites. To do so, we needed to be able to show that these data can be used to correctly locate ecotones or vegetation boundaries. From our initial analysis of this imagery, we found that this was feasible.

On Mt. Kenya, with the co-operation of the Kenyan Forest Health Management Centre, we established over 120 ground-located control points for interpretation of current vegetation pattern on Mt. Kenya (Fig. 1). These points were registered on the Landsat image shown in Fig. 1 to obtain a current vegetation map. The surveys were conducted along the three roads that climb Mt. Kenya and were well inside the altitudinal range of our sites used for evaluating reconnaissance imagery. The vegetation zonations seen on our own ground survey and those mapped in earlier studies by plant ecologists, are distinguishable using the reconnaissance imagery (an example of which is shown in Fig. 2), as are the



**Fig. 1** Landsat<sup>TM</sup> false colour composite, from 30 January 1995 (red = band4, green = band3, blue = band2). This satellite image shows the vegetation zones of Mt. Kenya. The study area is indicated by a rectangle. Vegetation zones are from Rehder *et al.* 1988):

- a) Montane Rain Forest occurring from 1500 to 2900 m altitude with Meru Oak (*Vitex keniensis*), East African Camphorwood (*Ocotea usambarensis*), East African Yellow-wood (*Podocarpus falcatus* and *P. latifolius*) and Parasol Tree (*Polyscias kikuyuensis*).
- b) Arundinaria alpina zone at 2200–3100 m altitude. This zone tends to have distinct boundaries, but may also be found mixed with species found in the montane zone. This species is not found on the dryer Mt. Kilimanjaro.
- c) Hagenia–Hypericum Forest zone found on wet soils and distributed as a thin ribbon between heathland and either bamboo or montane rain forest at altitudes of 2700–3200 m. This vegetation typically has a distinctive boundary that shows as a dark grey in this image. It is also occasionally found as island pockets within the heathland zone. Typical species include: East African Redwood (*Hagenia abyssinica*), *Hypericum keniensis*, and African Pencil Cedar (*Juniperus procera*).
- d) Heathland zone at an altitude of 2900–4000 m. The zone has two distinct communities: Ericaceous bush and open moorland. Ericaceous bush occurs throughout the altitude range of the heathland. Typical vegetation includes small trees, shrubs and scrubby vegetation, including *Nidorella arborea*, *Protea kilimandscharica*, *Philippia keniensis*, *Erica arborea*, groundsel (*Dendrosenecio brassica*), tree-groundsel (*Dendrosenecio johnsonii batticomei*), and *Lobelia keniensis*, along with occasional grassy tussocks. Open moorland occurs only in the wetter areas over an altitude range of 3100–3900 m and contains mostly tussock grasses such as *Carex monostachya*, *Festuca pilgeri* and *Alchemilla johnstonii*.
- e) Alpine zone found at 3900–4500 m. The boundary between the heathland and the alpine zone is not distinct. The species living in the two zones are similar and have overlapping altitudinal ranges. The transition from heathland to alpine zones is a gradual decrease in the density of the vegetation. The species that is strikingly unique in the alpine zone is the giant tree groundsel (*Dendrosenecio keniodendron*) which grows in a scattered fashion throughout the zone. In some of parts of this zone, *D. keniodendron* forms open groves called *Dendrosenecio* woodlands.
- f) Nival zone, which covers the altitude range from about 4500 m to the summit (5900 m for Mt. Kilimanjaro and 5200 m for Mt. Kenya).



**Fig. 2** Changes in vegetation zones in the Mt. Kenya analysis. The image in (a) is a portion of the 1984 data used. Maps shown in (b) and (c) are derived from interpretation of the 1984, &, 1993 data, respectively.

boundaries or ecotones between the different vegetation zones.

As a consequence of the similar climates and relative proximity to each other, the two East African mountains used in our study exhibited similar vegetation types and zones. The general vegetation zones at Mt. Kenya are discernible in the Landsat<sup>TM</sup> image of Fig. 1. The main difference between Mounts Kenya and Kilimanjaro is that a slightly drier climate at Mt. Kilimanjaro results in the absence of a bamboo zone that occurs at elevations between 2200 and 3100 m on Mt. Kenya.

The Mt. Kenya site used in this analysis is on the east side of the mountain, north-west of the Mt. Kenya Lodge near the terminus of the Chogoria Route. The site is located at an elevation of 3000–3200 m. The locations of the two Mt. Kilimanjaro study sites are near the Mawenzi Peak. The south site is about 3 km north of the Mandara Hut, which is located on the Marangu Route (37°30' E, 03°10' S). The north site is located on the north-east side of the Mawenzi Peak at 37°30' E, 03°02' S. The first site is located at an elevation of 2700–2900 m and the second is between 2700 and 3400 m elevations.

#### *Observed vegetation change on high-elevation tropical mountains*

Vegetation change was detected at all sites surveyed. The changes are of two types: (i) changes in vegetation type (or zone) due to vegetation migration; and (ii) a transition of sparse vegetation cover to a more dense vegetation cover, either with or without a shift in vegetation species. An example of our analysis results is shown in Fig. 2. Figure 2(a) is an example of the imagery used in this study. The zonal changes in the pattern and density of the vegetation can be seen easily in this image. Figure 2(b) and (c) are maps of change derived from comparison of such images from 1984 and 1993. These changes are consistent with the hypothesized increase in plant vigour resulting either from an increase in ambient CO<sub>2</sub> levels in the atmosphere or from other positive and simultaneous changes on all three sites.

On Mt. Kenya, the most striking change was observed along a boundary between heathland and *Hagenia-Hypericum* forest over a 9-year time period (January 1984 to March 1993). Figure 2(a) shows a portion of the

**Table 1** Mount Kilimanjaro North Site detailed change statistics

Initial vegetation	Type of change	Area (km <sup>2</sup> )	Area fraction (%)
Forest	Unchanged	4.267	17.6
Forest	To vegetated non-forest	0.088	0.4
Forest	To bare/sparse vegetation	0.002	0.01
Vegetated non-forest	Unchanged	11.987	49.6
Vegetated non-forest	To forest	0.530	2.2
Vegetated non-forest	to bare/sparse vegetation	0.555	2.3
Bare/sparse vegetation	Unchanged	1.359	5.6
Bare/sparse vegetation	To forest	0.116	0.5
Bare/sparse vegetation	To vegetated non-forest	5.277	21.8
	<b>Net vegetation change (increase)</b>	<b>5.366</b>	<b>22.2</b>

1984 reconnaissance imagery used for this analysis. A manual interpretation of the 1984 and the 1993 imagery resulted in the derived map products shown in Fig. 2(b), (c). These maps show the division of the vegetation zones, and indicate the area of vegetation change shown on Fig. 2(c). The change is seen as a movement of darker vegetation in the imagery, which is likely a consequence of a vegetation density change and possibly a change in dominant plant species. The most likely plant species candidates for the vegetation present at this change location are *Hypericum keniense*, *Erica arborea*, and *Philippia keniense*. Based on our interpretation of the imagery and our field visit, it was determined that this area of vegetation change has a canopy with characteristics similar to the thin ribbon of vegetation (*Hagenia-Hypericum* forest) that constitutes the interface between the bamboo and heathland vegetation zones. The same vegetation change was detected and mapped using civilian satellite images, Landsat<sup>TM</sup> MSS imagery from 24 January 1976 and Landsat<sup>TM</sup> from January 1995. From the analysis of the imagery, the estimated area of increase in the *Hagenia-Hypericum* vegetation type at this site over the time period from 1984 to 1993 is 1.28 km<sup>2</sup>.

Results from analyses at the Mt. Kilimanjaro sites were consistent with the Mt. Kenya results. For this analysis, images were digitized and georeferenced precisely to 1:50 000 scale maps obtained from the United Kingdom Ordnance Survey. The digitized images were entered into a geographical information system (GIS), and differences found using image brightness information, rather than the manual interpretation used for the Mt. Kenya analysis. The most pronounced vegetation increase again occurred in the vegetation transition area involving the heathland zone.

For the south site, four change parameters were included in the analysis results: vegetation increase, vegetation decrease, unchanged forest, and unchanged nonforest which includes both bare and nonforest vegetated areas. The study area experienced about a

17% net vegetation cover increase (0.216 km<sup>2</sup>) over the 1984–93-time period.

Analysis of all possible vegetation change combinations among forested, vegetated nonforest, and bare/sparse vegetation was performed on the data from the Mt. Kilimanjaro north site. Table 1 shows the area statistics for the nine different change classes for the time period between 1984 and 1993. The study area experienced about a 22% net vegetation increase (5.366 km<sup>2</sup>) over the 1984–93-time period.

## Conclusions

These studies clearly illustrate the capability of an archival network using reconnaissance imagery to collect primary data on vegetation change. Using these data, we were able to determine that the proposed high-elevation archival network should be able to detect both changes in ecotones and apparent increases in the vigour of vegetation within a vegetation zone.

Over the roughly 10-year period investigated, vegetation movement/change was detected at all of the sites included in this study. On Mt. Kenya, we detected movements of the boundary between the heathland and *Hagenia-Hypericum* forest. These changes amounted to very substantial (greater than 1 km<sup>2</sup>) shifts in vegetation zones over a decade. On Mt. Kilimanjaro, vegetation changes were most striking around the Mawenzi peak where significant vegetation change (filling in of bare ground and sparsely vegetated areas) was seen over approximately 20% of the area. These results may be consequences of climatic improvement at these elevations, the recovery of the vegetation from disturbance, or change in management policies in the two mountain parks. Certainly, the results are indicative of increased vigour in plant growth. The observed patterns of plant growth seen in this study are consistent with what one might expect from an increase in atmospheric CO<sub>2</sub>, if low partial pressures of CO<sub>2</sub> are limiting plant performance

at high elevations. Historical reconnaissance imagery can be used to determine changes in vegetation in remote locations and, thus, has considerable value to ecologists and biologists interested in fundamental observations on patterns of regional and global change. The changes observed for equatorial, high-altitude locations suggest a need to investigate the causes of such changes with additional studies of plant performance in these locations.

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